AIAA 2001-4051

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NASA Ames Research Center
Moffett Field, CA

AIAA Guidance, Navigation, and Control Conference
6 – 9 August 2001
Montreal, Canada

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Abstract

A concern in the transition from the current structured routing system to a future free routing system is the number and nature of conflicts generated. This paper analyzes the properties of air traffic conflicts under both these routing systems. Simulations of air traffic operations in Class A (18,000 ft and above) airspace across the contiguous United States were conducted using the Future ATM Concepts Evaluation Tool (FACET). Aircraft trajectories were generated based on initial conditions and flight plans obtained from real air traffic data over a 24-hour period. Free routes were modeled as great circle (direct) routes from origin to destination, and structured routes were constructed from real flight plans along the current system of air routes. The results indicate that, even in the absence of controller intervention, conflicts do not occur very frequently, with less than 30% of all aircraft experiencing even a single conflict. Of these aircraft, approximately 40% encountered more than one conflict. A near-linear relationship exists between the number of conflicts and the number of aircraft flying. The vast majority (over 80%) of conflicts are temporally isolated events that have no significant interaction with each other. It was also observed that, in the absence of controller actions, free routing operations have significantly fewer conflicts, involving a smaller number of aircraft, compared to current structured routing operations.

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Introduction

Potential conflicts routinely arise in air traffic operations when the separation between aircraft is predicted to drop below a specified minimum separation standard within the next several minutes. Timely action is required to maintain safety by resolving the conflict. Detection and resolution of potential conflicts currently represents a major portion of an air traffic controller's responsibilities, and conflict resolution advisories are a significant source of aircraft trajectory interruptions. It is therefore of interest to study the frequency and nature of conflicts in the current structured routing environment where aircraft fly along a system of fixed routes, as well as a future free routing system where aircraft fly along flexible user-preferred routes. The goal of this work is to compile a comprehensive set of statistics on conflict properties, to help guide future work in the area of conflict detection and resolution.

This paper analyzes simulated conflict data obtained from realistic air traffic scenarios based on initial conditions and flight plans constructed from real operational data. The objectives are to catalog salient properties of conflicts in general, and to determine any differences that may exist between conflicts found in free and structured routing operations. The nature and degree of interactions between conflicts are also studied in this work. References 1 – 4 describe some prior work on conflict properties.

Conflict Data Collection

The data collection for this study was conducted in an air traffic simulation environment known as the Future ATM Concepts Evaluation Tool (FACET).[5] The architecture of FACET strikes an appropriate balance between flexibility and fidelity; this feature enables FACET to model airspace operations at

the U.S. national level, and process over 5,000 aircraft on a single desktop computer running on any of a wide variety of operating systems. FACET is capable of modeling system-wide airspace operations over the contiguous United States. Airspace models (e.g., Center/sector boundaries, airways, arrival/departure routes, locations of navigation aids and airports) are available from databases. Weather models (winds, temperature, bad weather cells, etc.) are also available. A core capability of FACET is the modeling of aircraft trajectories. Using round-earth kinematic equations, aircraft can be flown along either flight plan routes or direct (great circle) routes as they climb, cruise and descend according to their individual aircraft-type performance models. Performance parameters (e.g., climb/descent rates and speeds, cruise speeds) are obtained from data table lookups. Heading and airspeed dynamics are also modeled.

A recording of Enhanced Traffic Management System (ETMS) data was made, covering a 24-hr period in March 2001. ETMS data includes track (position, speed, and heading) information, and flight plans from actual air traffic operations over the United States. Fig. 1 shows the ETMS aircraft count in contiguous U.S. airspace as a function of time. Over this 24-hr period, the ETMS data contained a total of 57,402 aircraft that flew in U.S. airspace. Of these, 37,926 aircraft (66%) operated in Class A airspace (at or above FL 180).
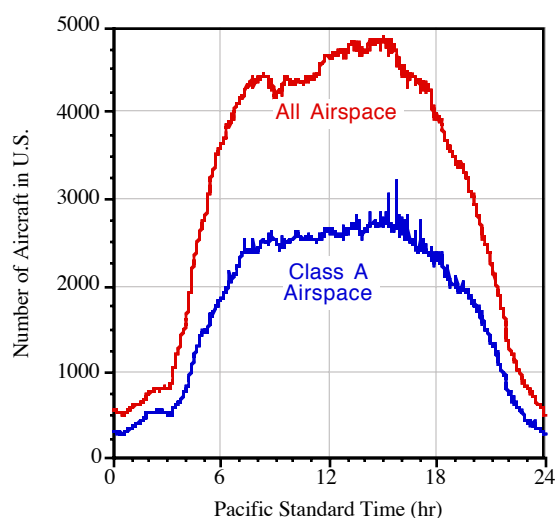
Fig. 1: Aircraft Count vs. Time for ETMS Data

The times and positions corresponding to each aircraft's first appearance in the ETMS data set were captured; they are referred to as birth points. The birth points provide realistic initial conditions for simulating trajectories in FACET to "fly" the aircraft to their destinations. Two sets of simulated trajectories were generated; it is noted that both simulation runs were made with zero winds. One simulation utilized real flight plan data from ETMS to fly each aircraft from its birth point to its destination, representing structured air traffic operations in the current system. In the other simulation, each aircraft was flown directly to its destination along a great circle route, representing free flight operations (valid for a constant wind field). In both simulations, each aircraft climbed directly to (and cruised at) the maximum altitude recorded in the ETMS data, and then descended to its destination. The climbs and descents were modeled using the aircraft performance database in FACET.

FACET's conflict detection and resolution module was turned off for the data collection; hence air traffic conflicts developed in the simulation as the aircraft flew along their routes. Data on these conflicts were recorded by FACET to a data file for post-processing to determine conflict properties. This data set contains information on conflict pairs (aircraft identification, latitude, longitude, altitude, speed, heading, and altitude-rate) at each simulation time step (every 15 sec). It is noted that these data are for conflicts that actually occurred (i.e., observed losses of separation) in the FACET simulation.

This work analyzes what would occur in Class A airspace (loosely referred to in the work as "en route" airspace), without any air traffic control actions. In actual terminal airspace operations (below FL 180), aircraft trajectories can be significantly different from those indicated by their flight plans due to numerous controller actions for arrival metering, sequencing, merging, etc. These controller actions generally have a separation assurance component built into them. Hence terminal airspace conflict data obtained from a flight plan based simulation would generally not be representative of real-world conflicts. Additionally, a significant percentage of operations below FL 180 are conducted under Visual Flight Rules (VFR), and it is not feasible to accurately simulate the trajectories of VFR traffic.

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The raw conflict data set obtained from FACET was first pruned by filtering out all conflict data involving aircraft below FL 180. The resulting data set contained all conflicts that occurred in en route airspace. Very short duration conflicts (less than 0.5 min) were then filtered out. This reduced data set was analyzed to determine the characteristic properties of air traffic conflicts for structured (flight plan) and free (great circle) routing.

Conflict Properties

The objectives of this work are to catalog various properties that characterize conflicts found in realistic air traffic scenarios, and to determine any significant differences in these properties between conflicts found in structured and free routing operations. The following conflict properties are analyzed in this study: (1) Number and frequency of conflicts and aircraft involved in conflicts; (2) Distributions of encounter angle, altitude-rates, conflict duration, and conflict intrusion; and, (3) Categorization of conflicts based on degree of interaction.

The third set of properties listed above reveals the nature and degree of interaction between conflicts. Consider an aircraft A that is involved in a conflict with aircraft B and then with aircraft C at certain times over its trajectory. If the temporal separation between conflicts A–B and A–C is larger than a threshold value T^* (derived from the average conflict time), then there is no significant interaction between these conflicts. Hence, the resolution of conflict A–B would generally not have a significant effect on conflict A–C. If the start of conflict A–C occurs within the time interval T^* following the end of conflict A–B, then the two conflicts have a weak interaction due to their close succession. Such a situation may arise if the nominal trajectory of aircraft A successively intersects the nominal trajectories of aircraft B and C within a short period of time. If the start of conflict A–C occurs before the end of conflict A–B, then the two conflicts have a strong interaction due to their temporal overlap. This can happen if the nominal trajectories of aircraft A, B, and C converge towards a small region of airspace. If a weak/strong interaction exists, the resolution of conflict A–B would generally have a corresponding weak/strong effect on conflict A–C. A schematic representation of the three conflict categories is shown in Fig. 2.

While the illustration is for two conflicts, the classification can be extended to cases with more than two conflicts by applying the criterion at both the start and end of each individual conflict. In such cases, the interaction level of a conflict is
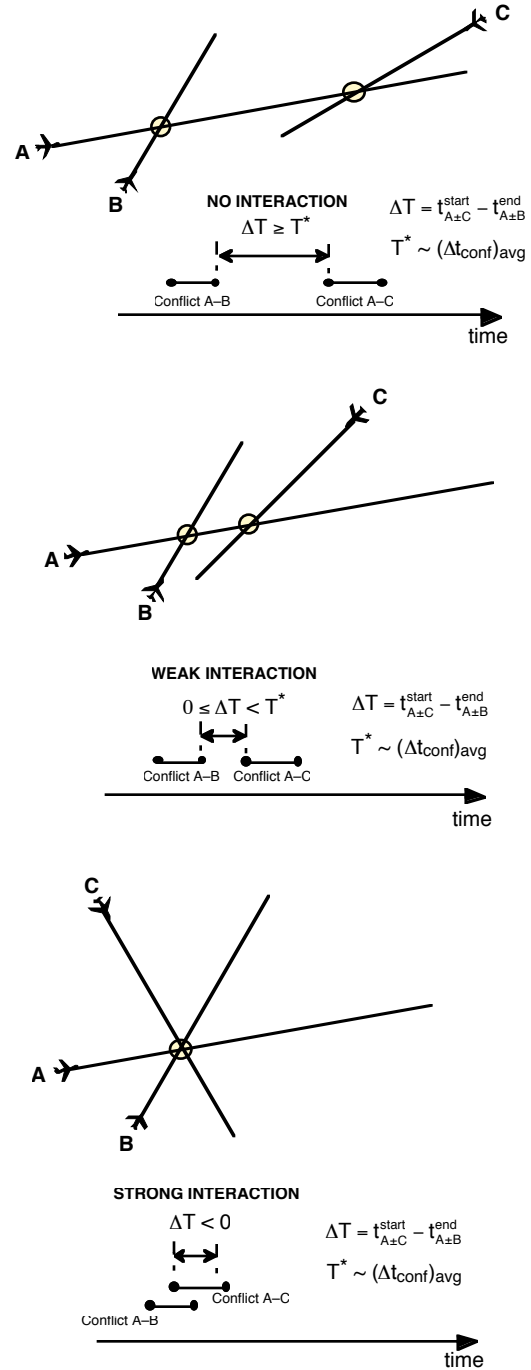
Fig. 2: Conflict Interaction Categories

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classified as "None" or "Strong" only if the corresponding criterion is satisfied at both the start and end of the conflict; otherwise, it is classified as "Weak." For example, the overall interaction level of a conflict with no interaction at the start and strong interaction at the end is classified as "Weak."

Results

The filtered conflict data from FACET were post-processed to determine the various properties described in the previous section. Fig. 3 shows the total number of conflicts in en route U.S. airspace along with the number of aircraft involved in these conflicts, for structured (flight plan) routing and free (great circle) routing. It is evident that free routing results in significantly fewer conflicts than flight plan routing; this trend is consistent with data reported in Ref. 1 (which focuses primarily on the spatial distribution of conflicts, and flight delays). Relative to structured routing, the number of free routing conflicts is about 13% smaller, while the corresponding number of aircraft involved in conflicts is about 6% smaller. It is noted that of the 37,926 aircraft in en route U.S. airspace over the 24-hr period of interest, only 27% were ever involved in a conflict for free routing, vs. 29% for structured routing. Fig. 3 shows that the number of conflicts is significantly greater than one-half the number of conflicting aircraft. This indicates that a significant number of aircraft were involved in more than one conflict.

Fig. 4 shows the number of conflicts encountered by those aircraft that ever experienced a conflict. It can be seen that approximately 40% of conflicting aircraft encountered more than one conflict. Only small differences are observed between the distributions for free and structured routing conflicts.

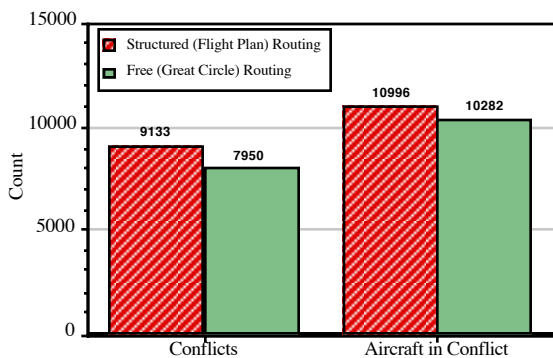Fig. 5 shows the instantaneous conflict count in en
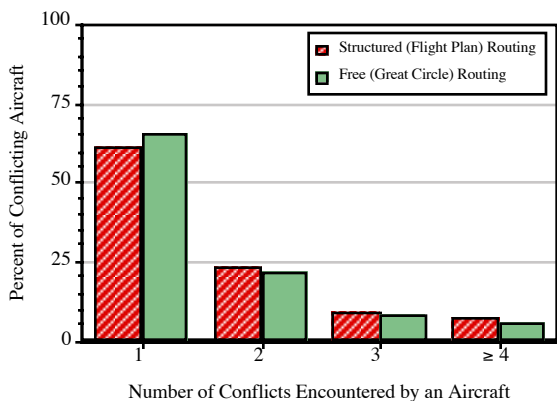

Fig. 3: Counts of Conflicts and Aircraft
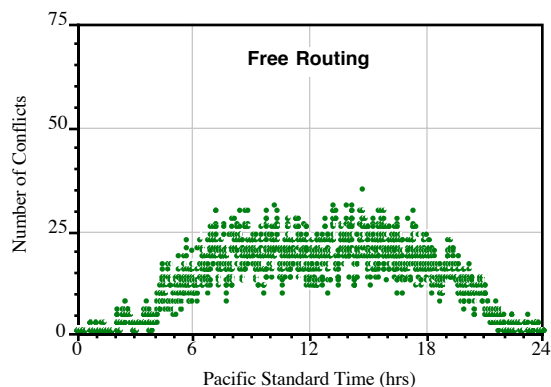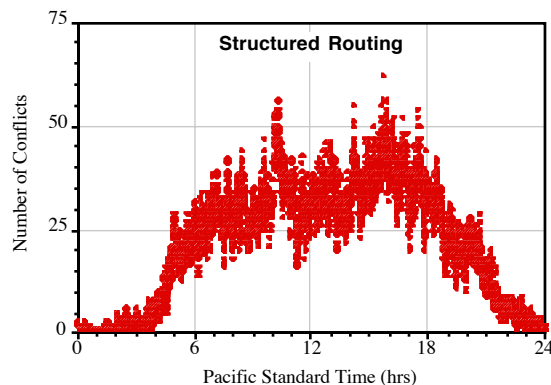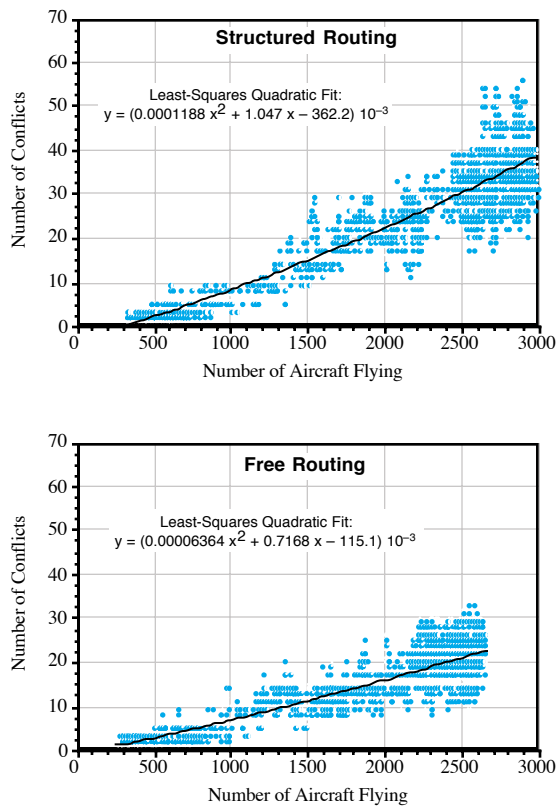

Fig. 4: Number of Conflicts per Aircraft

Fig. 5: Conflict Counts vs. Time

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route U.S. airspace for structured and free routing. It can be seen that at any instant of time, the conflict count for free routing is generally less than that for structured routing. The instantaneous number of conflicts occurring at any time in en route U.S. airspace is less than 35 for free routing, and less than 65 for structured routing.
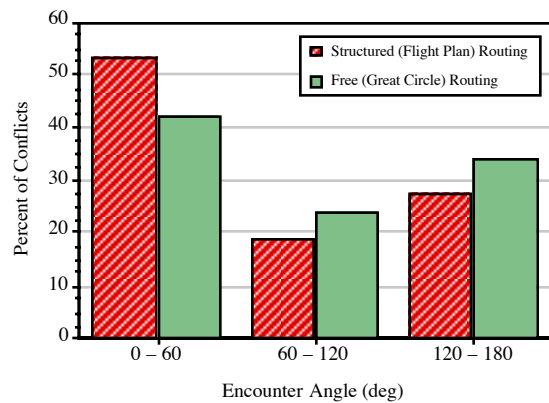
Fig. 6 shows the number of conflicts as a function of the number of aircraft flying, for structured and free routing. Each dot represents a point in time when there was at least one conflict in progress; the x-coordinate is the number of aircraft flying in en route airspace at that time, and the y-coordinate is the number of conflicts in progress in en route airspace at that time. It can be seen that the number of conflicts increases with the number of aircraft flying, as expected. The solid curves represent least-squares quadratic fits to the data points. The curves and their equations indicate that the nonlinearities are quite small. It should be noted that the data in Fig. 6 reflect the flight schedule and city-pair distributions found in
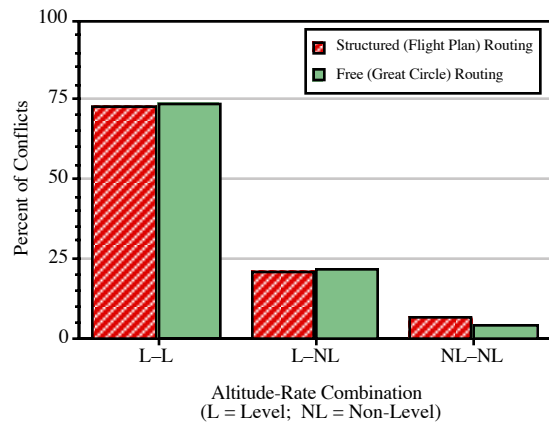
current air traffic operations. Purely randomized traffic scenarios would typically exhibit a strong quadratic relationship between the number of conflicts and the number of aircraft flying.

Figs. 7 – 9 show the distributions of some key conflict parameters: encounter angle, altitude-rate combination (both aircraft level, one aircraft non-level, both aircraft non-level) and conflict time. It can be seen that structured routing conflicts are characterized by smaller encounter angles. There is a larger percentage of structured routing conflicts in the 0 to 60 deg range, possibly due to aircraft following each other along a fixed-route network . No significant difference is observed in the altitude-rate distributions; both types of routings show approximately 75% level-level conflicts. The conflict time distributions indicate that structured routing has a higher percentage of


Fig. 7: Distribution of Encounter Angle

Structured Routing

Least-Squares Quadratic Fit:
$y = (0.0001188 \, x^2 + 1.047 \, x - 362.2) \, 10^{-3}$

Fig. 6: Conflict Counts vs. Aircraft Counts

Free Routing

Least-Squares Quadratic Fit:
$y = (0.00006364 \, x^2 + 0.7168 \, x - 115.1) \, 10^{-3}$

Fig. 8: Distribution of Altitude-Rates

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longer-duration conflicts, possibly reflecting the higher percentage of shallow encounter angle conflicts that are typically longer in duration. The mean conflict time is approximately 3 minutes for structured routing conflicts, and approximately 2 minutes for free routing conflicts.
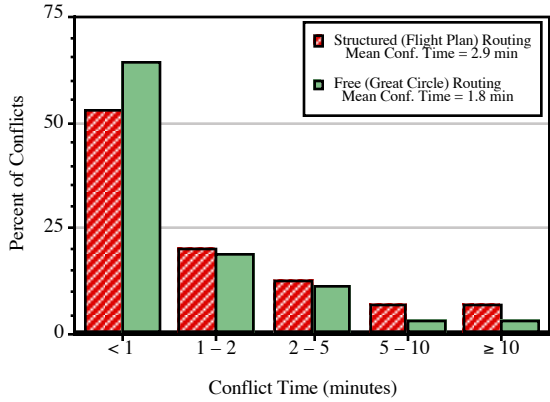
Fig. 9: Distribution of Conflict Time

Another key conflict parameter is the severity or intrusiveness of the conflict, which may be quantified by three intrusion parameters, as described below.   The horizontal intrusion parameter, *HIP*, is defined as:

$$HIP = \left\{ 1 - \min_{t_{SOC} \le t \le t_{EOC}} \left(\frac{\Delta s(t)}{S_{std}} \right) \right\} \qquad (1)$$

where S_{std} is the horizontal separation standard, equal to 5 nm in en route airspace, and $\Delta s(t)$ is the horizontal separation at time t over the duration of the conflict, i.e., from start-of-conflict time, t_{SOC}, to end-of-conflict time, t_{EOC}.
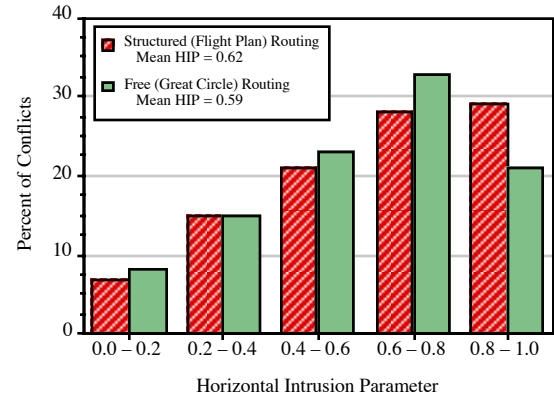
Similarly, the vertical intrusion parameter, *VIP*, is defined as

$$VIP = \left\{ 1 - \min_{t_{SOC} \le t \le t_{EOC}} \left(\frac{\Delta h(t)}{H_{std}} \right) \right\} \qquad (2)$$
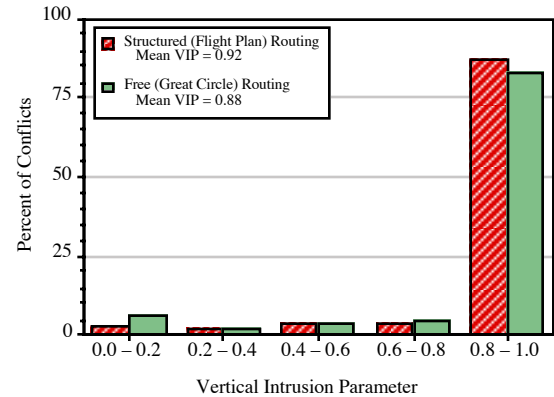
where H_{std} is the vertical separation standard, equal to 1000 ft (or 2000 ft if both aircraft are above FL 290), and $\Delta h(t)$ is the vertical separation at time t over the duration of the conflict.
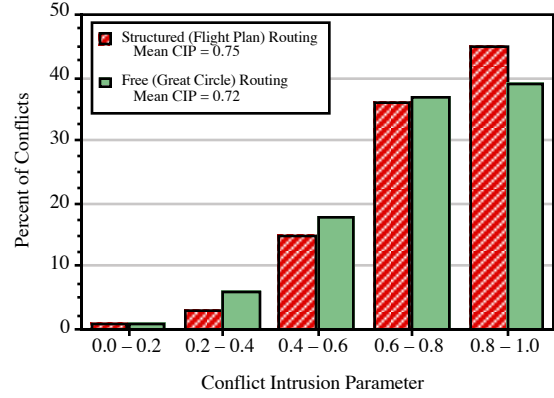
Fig. 10a: Distribution of Conflict Intrusion

Fig. 10b: Distribution of Horizontal Intrusion

Fig. 10c: Distribution of Vertical Intrusion

The total (horizontal plus vertical) conflict intrusion is given by the conflict intrusion parameter, *CIP*, defined as:

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$$CIP = \left\{ 1 - 0.5 \min_{t_{FLS} \le t \le t_{EOC}} \left(\frac{\Delta s(t)}{S_{std}} + \frac{\Delta h(t)}{h_{std}} \right) \right\} \qquad (3)$$

It is noted that for a given conflict, the times associated with HIP, VIP, and CIP are not necessarily the same.

Figs. 10a–c show distributions of the conflict intrusion parameter, along with the corresponding horizontal and vertical intrusion parameters. It is noted that larger values indicate higher levels of intrusion, e.g., $CIP = 1$ corresponds to a collision. Fig. 10a shows that although the average value of CIP is roughly the same for both free and structured routing conflicts, the distributions are significantly different. Free routing conflicts have a substantially smaller percentage of high-degree conflict intrusions ($0.8 < CIP \le 1$) than structured routing conflicts. It can be seen from Figs. 10b,c that this difference arises primarily from the horizontal dimension of the conflicts. The average value of HIP for both free and structured routing is roughly the same, but the distributions are different and exhibit trends similar to those observed for CIP. Fig. 10c shows similar distributions of VIP for free and structured routing, with similar mean values. The large values of VIP are attributed to the fact that most conflicts in en route airspace occur between aircraft flying at the same altitude, corresponding to $VIP = 1$.

Fig. 11 shows the results of categorizing conflicts based on the level of interaction. A temporal separation threshold (T^*) of 2 minutes was used to identify non-interacting conflicts; this value was chosen because it is roughly equal to the average

duration of all conflicts (free and structured routing) found in this study. It is recalled that conflicts with strong interaction are those that have a temporal overlap.

It can be seen from Fig. 11 that the vast majority of en route conflicts have no significant interaction. About 8% of free routing conflicts and 16% of structured conflicts have some degree of interaction with other conflicts.

Conclusions

A simulation study of conflicts in structured and free routing operations has been conducted. The simulations were based on initial conditions and flight plans obtained from real traffic data. Various conflict properties were analyzed, including the degree of interaction between conflicts.

Results were obtained using 24 hours of ETMS data for en route (Class A) U.S. airspace. Compared to structured routing, the total number of conflicts for free routing operations is significantly (13%) lower, while the corresponding number of aircraft involved in conflicts is slightly (6%) lower. Less than 30% of aircraft ever experienced a conflict. Of these aircraft, approximately 40% encountered more than one conflict. It was observed that a near-linear relationship exists between the number of conflicts and the number of aircraft flying. The distributions of certain conflict parameters (e.g., encounter angle, conflict intrusion) show some differences across the two types of routings. A study of interaction between conflicts reveals that more than 80% of conflicts are temporally isolated events that have no significant interaction with other conflicts. It was observed that 16% of structured routing conflicts have some level of interaction, compared to 8% for free routing conflicts.
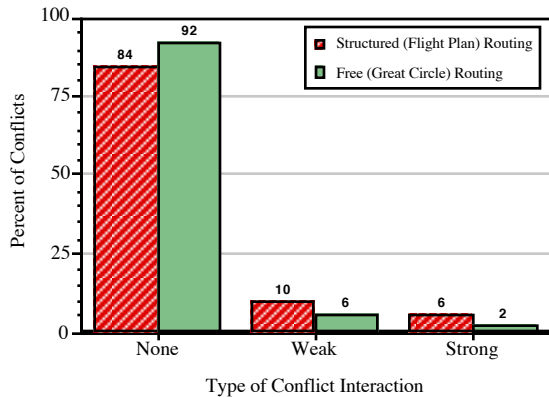
Acknowledgments

Fig. 11: Conflict Interaction Categories

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